SIMULATION OF A ROBOTIC BIRD

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Abstract: In this paper it is studied the dynamics of the robotic bird. The system performances are analyzed in terms of time response and robustness. It is study the relation between the angle of attack and the velocity of the bird, the tail influence, the gliding flight and the flapping flight. In this model, a bird flies by the wind beat motion or using its tail down. The results are positive for the construction of flying robots. The development of computational simulation based on the dynamic of the robotic bird that should allow testing strategies and algorithms of control.

Keywords: robotic, bird, control, dynamic, aerodynamics.

1. INTRODUCTION

Life in the Earth has appeared approximately at 2.5 billions of years, as a result of some physicals and chemicals processes, and evolved for the today existing species. One of those species is the bird that derived from a trunk of reptiles about 150 million years ago, at the same time of the first mammals. In the group of vertebrate animals, the birds are one of the most numerous, being found in almost everywhere in the world. They have many similar characteristics to the reptiles but they are different from all the other animals because of their feathers (Cianchi, *et al.* 1988). and other unique characteristics studied (Kenneth, Randall, and Terry Dial *et al*. 2006).

Everything about a bird is made for flight. In order to simulate and implement a robotic bird we would need to consider every single physical aspect.

Nowadays, robotics is an area extremely requested growing day after day. A robot can be defined as a programmable, self-controlled device consisting of electronic, electrical, or mechanical units. More generally, it is a machine that functions in place of a living agent. In this line of thought the idea of constructing robots that resembles to animals is already being implemented. Having as inspiration the behaviors of the animals, some works have been developed with the purpose of implementing similar robotic behaviors. Examples of some robot-animals already build are spiders (Vallidis *et al.* 2001) and snakes (Spranklin *et al*. 2006). Both of them require an extended study of the physics and behavior of the real animals. Other interesting works focus specific characteristics of animals applying new technologies such as morphing materials in order to create wings (Manzo *et al*. 2006).

Our objective is to apply the knowledge already acquired, with the study of the state of the art, to simulate and construct a robot that resembles to a bird.

2. STATE OF THE ART

This work implements a system that includes a physical and dynamic model of a bird, in the perspective of (Zhu, Muraoka, Kawabata, Cao, Fujimoto and Chiba *et al*. 2006), that use a set of equations to simulate the behavior of a bird, using a real time animated model taking aerodynamics into consideration. In this model, a bird flies by the wing beat motion, using its tail feathers. Besides, the trajectory is established by determined points in the space adjusting the bird's orientation and flapping such that the bird passes through these points in sequence. This allows the bird to fly along an arbitrary path.

A method of producing realistic animations from numerical solutions is given for generic bird models with various levels of complexity (Parslew *et al*. 2005). The study describes the development of models, implemented in the analysis of flapping flight, balancing the scientific analysis and model-based animation. The presented results show numerical data and visual simulations able to produce realistic flapping flight with physical strong foundations. The aerodynamic coefficients of lift and drag are based on the Blade-Element Theory. This method requires an input of the angle of attack, along with the key aerodynamic properties of the wing in order to determine the lift and drag coefficient.

Birds' tails also play an important aerodynamic role in mechanical flight power and flight performance (Evans, Rosén, Park and Hedenström *et al.* 2001). Theory provides a conventional explanation for how bird's tail works. In (Zhu, Muraoka, Kawabata, Cao, Fujimoto, and Chiba *et al*. 2006) the influence of the tail and feathers is taken in consideration.

The paper is organized as follow. Section three provides an overview of the physical structure. The kinematics of the bird is referenced in section four. In section five we describe the bird dynamics implemented in our model. The study of flight is developed in section six. In section seven we will show some dynamical analysis from the point of view of the simulator. Finally, outlines the main conclusions.

3. PHYSICAL STRUCTURE

In order to visualize the behavior of the bird, while in simulation, we developed a 3D model in *AutoCAD* inspired in a seagull as can be seen in Fig. 1. Each adjacent part with different colors corresponds to individual elements connected through joints.

For simplicity, the structure of the wings will be defined in the sense of a human arm, using the terms arm and hand accordingly. The corresponding wing joints will be termed the shoulder and wrist.

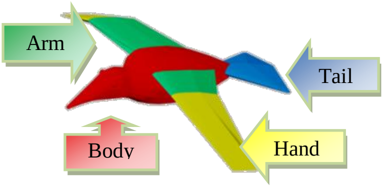


Fig. 1. 3D model of the robotic bird.

Table 1. Some characteristics of different birds

	Weight [grams]	***Wing Area [cm^2]***	***Maximum Velocity [m/s]***
Common Tern	117	500	7.8
Black-Headed Gull	235	750	9
Seagull	374	1150	9.2
Royal Tern	480	1080	10.7
Herring Gull	960	1810	11.7
Great Skua	1378	2140	12.9
Great Blacked-Backed Gull	1959	2720	13.6
Sooty Albatross	2857	3400	14.7
Wandering Albatross	8878	6200	19.2

We can subdivide two types of flight: quasi-steady and unsteady states. For larger birds the flights can be approximated by quasi-steady state assumptions because their wings flap at lower frequency during cruising. This means the wingtip speed is low compared to the flight speed. Thus larger birds, such as eagles and seagulls, tend to have a soaring flight. Their wings behave closely to fixed-wings. On the other hand, smaller birds and insects fly in an unsteady state regime (Colozza *et al.* 2007) in which their wingtip speed is faster that their flight speed.

The forces and flows around a flapping wing are still a challenge in fluid dynamics (Wang *et al.* 2005).

Others characteristics from real birds in consideration to simulate the bird flight besides the stability can be seen in Table 1.

4. KINEMATICS

With this model we analyzed the bird flight movement and its behavior in different states such as taking off, flying with twists and turns, etc. Through these studies of flying motion, we obtained initial valuable specifications which helped us chose the initial mechanical design (Fig. 2).

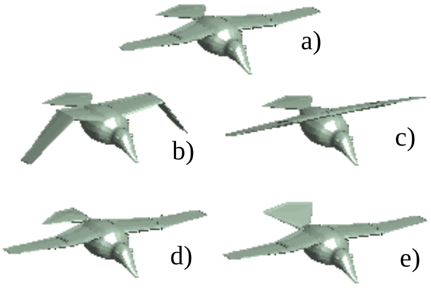


Fig. 2. a) Bird geometry, b) Wing flapping, c) Wing twisting, d) Tail twisting, e) Tail bending.

In this way, we estimated the location of every joint in the robot. The multi-link model is shown in Fig. 3. The number of joints has been reduced when compared with a real bird, but this mechanical structure gives us a good mobility. The joints are distributed as follows: two in the shoulder, one in the wrist and two in the tail. Differently from all the others, the joint in the wrist is not a controlled joint. It is a mechanical spring mechanism that allows a movement of the wing similar to real birds. This structure will provide a good mobility having a total of six controlled joints.

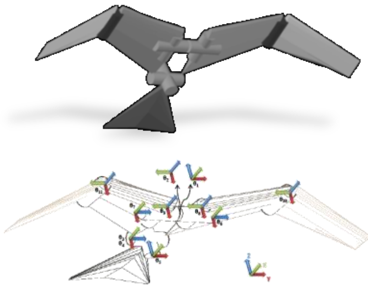


Fig. 3. Kinematic structure of the system.

In order to implement the animation of the bird in MatLab we had followed the Denavit-Hartenberg (D-H) notation (Denavit and Hertenberg *et al.* 1955) to represent frame (joint) coordinates for a kinematic chain of revolute and translational joints.

The next equation shows the homogeneous transformation $\mathbf{A_i}$. This will be a D-H matrix represented by a product of four fundamental transformations.

$$\mathbf{A_i} = \mathbf{R_{\theta i}}.\mathbf{T_{di}}.\mathbf{R_{\alpha i}}.\mathbf{T_{\alpha i}} \qquad (1)$$

where $\mathbf{R}_{\theta i}$ and $\mathbf{T}_{\theta i}$ are, respectively, the matrix rotation and matrix translation in *x*-axis and $\mathbf{R}_{\alpha i}$ and $\mathbf{T}_{\alpha i}$ are, respectively, the matrix rotation and the matrix translation in *z*-axis.

With a series of D–H matrix multiplications and the parameter table, the final result is a transformation matrix from some frame to the initial frame.

5. BIRD DYNAMICS

The relative wind acting on a wing produces a certain amount of force which is called the total aerodynamic force. This force can be resolved into components, called Lift and Drag (Fig. 4).

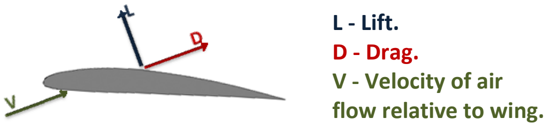


Fig. 4. Force acting on the wing.

The Lift – *L* (2) is the component of aerodynamic force perpendicular to the relative wind and the Drag – *D* (3) is the component of aerodynamic force parallel to the relative wind. Those components can be expressed by the following formulae:

$$L = \frac{1}{2}.\rho.v_{\infty}{}^{2}.S.C_l(\alpha) \qquad (2)$$

$$D = \frac{1}{2}.\rho.v_{\infty}{}^{2}.S.C_d(\alpha) \qquad (3)$$

The Lift and Drag on the wing depends on the wing area *S*, the density of air *ρ*, the velocity of the air flow relative to the wing v_∞ and the Lift and Drag coefficients C_l and C_d respectively, expressed as functions of the angle of attack *α*.

The Lift and Drag coefficients depend on the shape of the airfoil and will alter with changes in the angle of attack and other wing trimmings. The characteristics of any particular airfoil section can conveniently be represented by graphs showing the amount of lift and drag obtained at various angles of attack, the lift-drag ratio, and the movement of the center of pressure.

Similarly to Parslew *et al.* 2005 we adopted the blade-element theory representing the Lift (4) and Drag (5) coefficients as functions of the angle of attack of the local wind (Fig. 5).

$$C_l = C_{lmax}.sin(2.\alpha) \qquad (4)$$

$$C_d = C_{do} + C_{dmax}.sin^2(\alpha) \qquad (5)$$

The wing aerodynamics properties of maximum lift $C_{l\max}$ and drag $C_{d\max}$ coefficients and zero drag C_{d0} coefficient since we are not considering any particular wing aerodynamics at this point.

$$C_{lmax} = 2 \qquad (6)$$

$$C_{do} = 0.05 \qquad (7)$$

$$C_{dmax} = 1 \qquad (8)$$

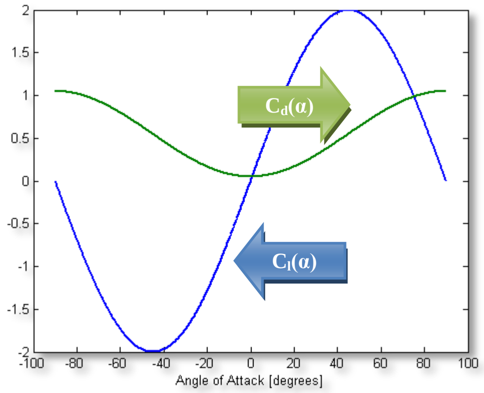


Fig. 5. Lift and Drag coefficients functions.

6. STUDYING THE FLIGHT

6.1. Gliding Flight

Some birds take advantage of the air currents to remain aloft for long periods without flapping their wings. The bird's aerodynamic characteristics determine how far and for how long it can glide, and how successfully it can soar in moving air. Those aerodynamic characteristics can be optimized by the bird in the flight by changing the wing spans and wing areas.

For optimal gliding a bird's wing must maximize lift and minimize drag. As a rule, the smaller the bird, the shorter the distance it can glide and the faster it sinks.

During gliding the wings are stretched out stiffly. A good glider travels a long way horizontally with minimum loss of height, but eventually loses altitude due to the pull of gravity. The efficiency of a glider can be measured by calculating the angle between the track of its motion and the horizon. This angle depends not upon the weight of the bird but rather upon the forces of lift and drag, through wing shape does have some influence.

6.2. Flapping Flight

Aerodynamics involving flapping wings differs in many ways from conventional aerodynamics, but some conventional rules apply. A conventional airplane uses a propeller for thrust and fixed wings for lift. An ornithopter's wing must provide both of these forces. The forces on the wing (Berg and Rayner *et al.* 1995) vary throughout the flapping cycle as we will see in the dynamical analysis. On the down stroke air is displaced in a downward and backward direction. On the upstroke, the situation is reversed being the area of the wing smaller than before in order to make a positive global lift. In order to make the area of the wing smaller, birds uses different techniques such as manipulating the wings. To simplify we considered the area in the upstroke half the area in the down stroke. The science behind flapping flight is complex and we are still studying it.

6.3. Tail Influence

The precise use of the tail in flying birds has not been thoroughly documented (Zhu, Muraoka, Kawabata, Cao, Fujimoto and Chiba *et al*. 2006). The tail feathers are instrumental in stabilizing the flight, changing the direction of the forward movement, compensating for the lift force, and acting as a brake when the bird lands. We are using the tail in order to cause a drag force changing the moment of the bird and, consequently, producing a rotation around an axis equal to the axis of rotation of the tail. That is, if the tail is bending up, the bird will rotate around the same joint bending up too. If the tail bends up and twists right for example (Fig. 6), the bird will then rotate around both the joints of the tail up and right. The angle of rotation of the tail is always relative to the movement of the bird.

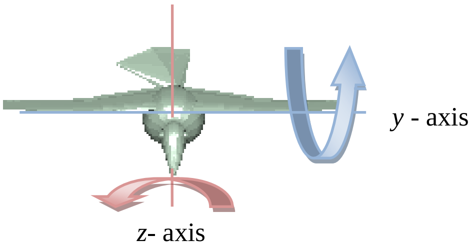
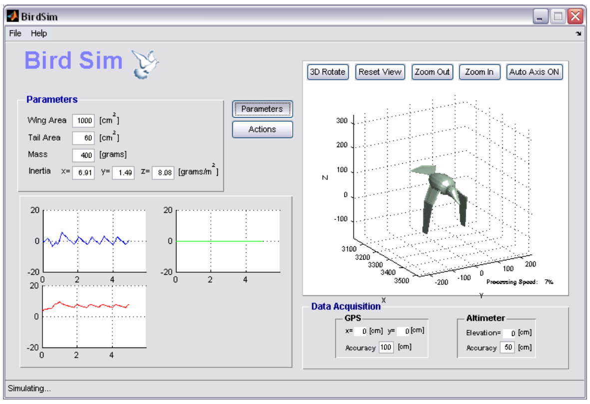


Fig 6. Action of bird tail.

7. DYNAMICAL ANALYSIS

We have undertaken a dynamical analysis to test the validity of the system model. In order to change easily the parameters (*e.g.*, wing area, weight) we build a user friendly interface (Fig. 7) that allows us to watch the bird animation while the charts of the velocities in the three axes are constructed.



Parameters

Wing Area 1000 [cm^2]
Tail Area 60 [cm^2]
Mass 400 [grams]
Inertia x= 6.91 y= 1.49 z= 8.08 [grams/m^2]

Processing Speed: 7%

Data Acquisition

GPS
x= 0 [cm] y= 0 [cm]
Accuracy 100 [cm]

Altimeter
Elevation= 0 [cm]
Accuracy 50 [cm]

Simulating...

Fig 7. Simulator SIRB.

We will initially show some results of the bird dynamics around the gliding flight. These results are based on different parameters of the bird.
In each simulation the wind has a constant velocity of v = 5.0 m/s against the movement of the bird that has an initial velocity of v_0 = 4.0 m/s. We will change the weight and area of the wing parameters in order to analyze the bird dynamics. The initial parameters are a total weight of m = 0.4 kg and the wing an area of $S = 10^{-3}$ m^2. The tail will have the influence in each experiment being parallel to the movement when flying straight and it will have a small fixed degree relative to the movement when flying down or up, in order to make a soft inclination on the bird.

7.1. Analyzing the Gliding Flight

The first charts (Figures 8 to 11) show the relation between the angle of attack and the velocity of the bird while gliding in a straight line.
In order for the bird to fly in a straight line without flapping its wings he needs to change continuously the angle of attack to keep a vertical resulting force equal to zero. The angle of attack will then increase increasing the Lift and the Drag forces (Fig. 5). An higher Drag force results in the reduction of the velocity. This process stops when the velocity reaches zero since we do not want the bird to be dragged by the wind. In Figures 8 and 9 we increased the weight of the bird by Δm = 0.1 kg for each experiment. As can be seen, straight, increasing the weight will requires a higher angle of attack in order to fly. The velocity does not change dramatically since the Drag force does not increase significantly for angles of attack lower than 20º (Fig. 6). Moreover, we verify that if the angle of attack increases the velocity decreases less than previously.

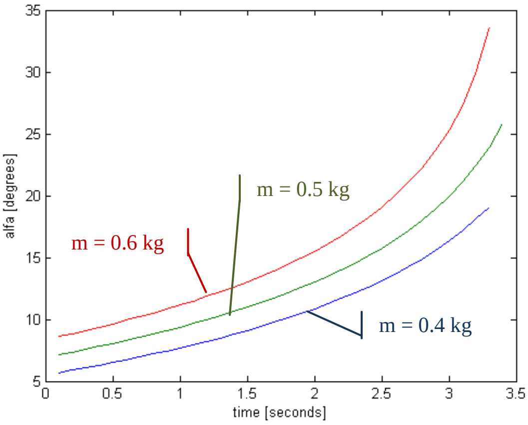


Fig. 8. Bird gliding straight changing the weight - angle of attack *versus* time.

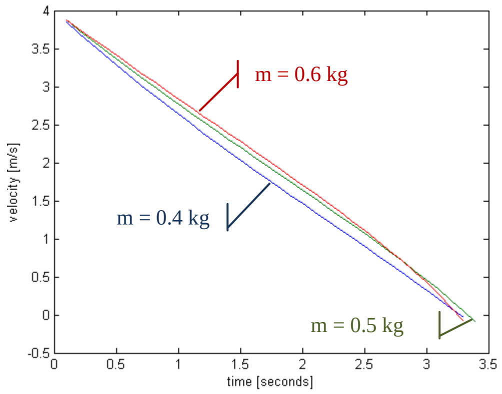


Fig. 9. Bird gliding straight changing the weight – velocity *versus* time.

In the next charts (Figures 10 and 11), we change the area of the bird increasing it by $\Delta S = 0.1\ 10^{-3}\ \text{m}^2$ for each experiment. As expected, increasing the area of the wing the bird wind is able to glide in a straight line with a smaller angle of attack. The velocity does not change significantly.

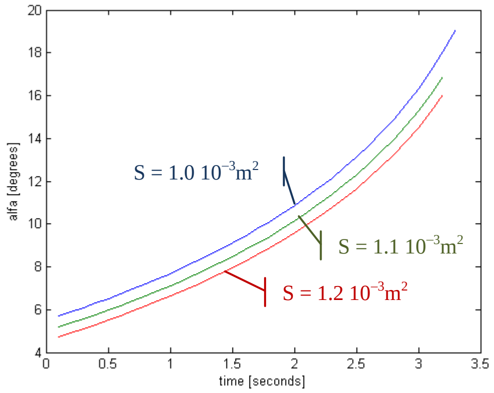


Fig. 10. Bird gliding straight changing the wing area - angle of attack *versus* time.

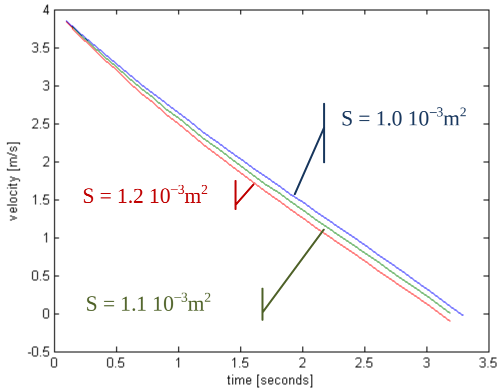


Fig. 11. Bird gliding straight changing the wing area – velocity *versus* time.

The second experiment (Figure 12 to 16) shows the horizontal (v_x) and vertical (v_z) velocities of the bird as well as the vertical distance realized while the bird is gliding down a vertical distance of 5.0 meters consider an angle of attack of 5.0 degrees in both wings.

As it can be seen in Fig. 12 the bird oscillates when gliding down, without changing the angle of attack. As the bird goes down the horizontal velocity increases as well as the Lift force. There is an instant where the resulting vertical force is zero and the bird moves straight until it as not enough horizontal velocity. When the horizontal velocity decreases there is no more balance between the vertical forces and the bird goes down again.

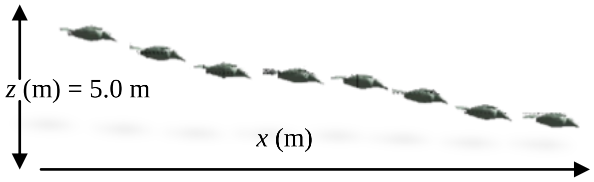


Fig. 12. Bird gliding down - sequence of images in *xz* plane.

Like we have done before, we firstly increase the weight of the bird (Figures 13 and 14). We see that if we increase the weight of the bird, and since we are not changing the angle of attack and the bird is gliding down, the weight will help the movement. The amplitude of the velocity will then increase and the bird will reach is target faster (approximately 2.5 seconds faster for each extra $\Delta m = 0.1$ kg of weight).

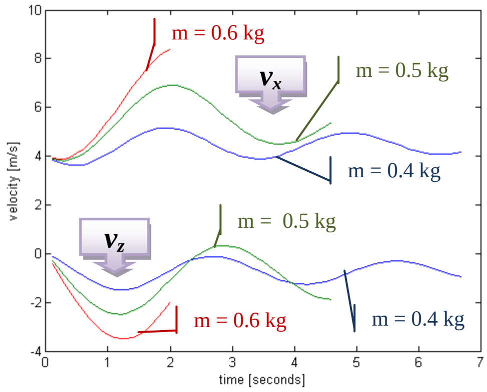


Fig. 13. Bird gliding down changing the weight – velocities *versus* time.

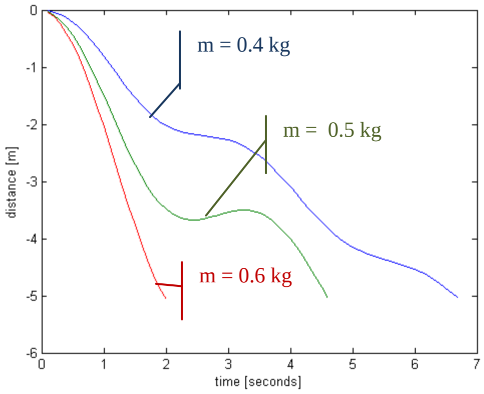


Fig. 14. Bird gliding down changing the weight - vertical distance *versus* time.

However, if we repeat the experiments, but increasing the area of the wings then the results will be considerably different.

The bird will take longer to reach the 5.0 meters as one should expect (Fig. 15). Both velocities, particularly the horizontal one, have smaller oscillations, but where we can truly see the difference is in the vertical movement (Fig. 16) of the bird.

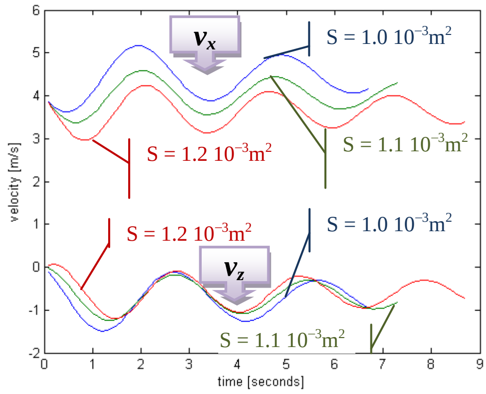


Fig. 15. Bird gliding down changing the wing area – velocities *versus* time.

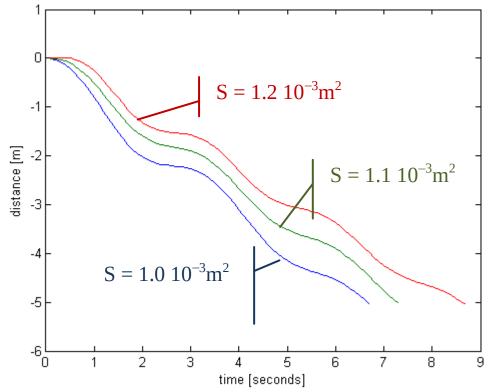


Fig. 16. Bird gliding down changing the wing area - vertical distance *versus* time.

The movement will be more linear and the bird will not go straight during so long as previously. In fact, the only thing that will happen is a decrease of the vertical velocity, but the bird will always go down.

7.2. Analyzing the Flapping Flight

Analyzing the flapping flight is not as simple as the gliding flight. We have implemented three *PID* controllers in order to control the flapping velocity of the wings, based on the error of the horizontal and vertical velocities relative to a constant reference.

Using the *PID* with experimental parameters for the different controller gains and ignoring the *y*-axis velocity for now we obtained good results for the gains shown in the next table:

Table 2. Controllers parameters obtained experimentally

	Kp	*Ki*	*Kd*
Horizontal Velocity	1/6	1/6	0
Vertical Velocity	6	6	0

It is good to see that our first priority is to keep the same altitude. The horizontal velocity may have some changes if needed in order to keep the bird flying in a straight line.

In our case, to comparing easily with the experiments developed before, we will have a reference of $v_x = 4$ m/s in the horizontal velocity v_z =and 0.0 m/s in the vertical velocity (to keep the same altitude).

Following the same analysis we change the weight and wing area parameters. The Figures 17 and 18 show how the velocities and vertical distance react while changing the bird weight.

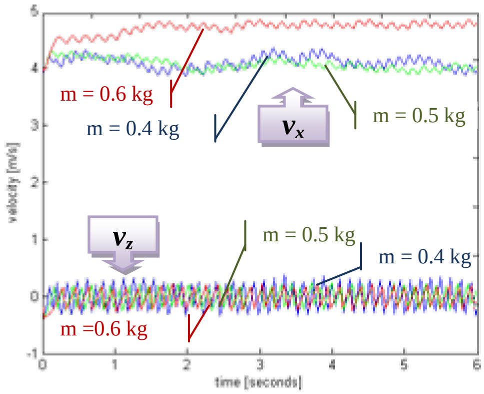


Fig. 17. Bird flapping straight changing the weight – velocities *versus* time.

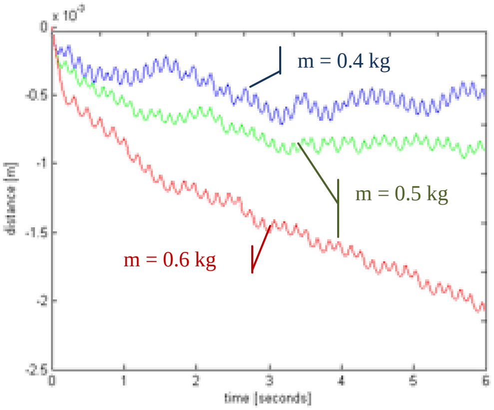


Fig. 18. Bird flapping straight changing the weight - vertical distance *versus* time.

With this closed loop controller the bird will fly in a quasi-steady state having a good response to our objective. Unfortunately, with m = 0.6 kg the bird can not keep the same altitude with the velocity of v = 4.0 m/s, therefore, so he tries to gain more horizontal velocity.

We can clearly see in Fig. 18 that the bird will loose altitude, something like 1 mm in 6.0 seconds, for a weight of m = 0.5 kg. In order to keep the same altitude the bird could be corrected after some time by changing the continuously the angle of attack.

The next experiment shows what would happen if the bird have bigger wings.

In Fig. 19 we can see that the bird does need to travel with a velocity of v = 4.0 m/s to fly in a straight line. He will then reduce the velocity of flapping wings wasting less energy to keep the same altitude. In Fig. 21 we can see the trajectory made by the bird.

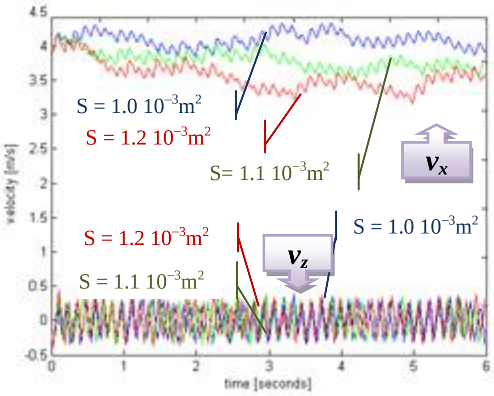


Fig. 19. Bird flapping straight changing the wing area - velocities *versus* time.

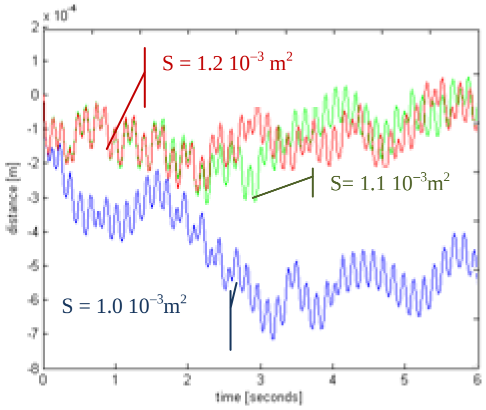


Fig. 20. Bird flapping straight changing the wing area - vertical distance *versus* time.

We can see that, for a wing area larger than S = 1.1 10^{-3}m^2 the bird will doesn't loose altitude even flying with a velocity lower than the reference. This means that bigger birds are able to travel for greater distances with a quasi-steady state flight wasting less energy than little birds.

Limiting the flapping velocity of wings from 0.0 flaps/s to 4.0 flaps/s we will obtain the following graphic (Fig. 20 for the initial parameters of the bird).

The controllers will act on the wing speed with a small chart fixed time step in order to prevent instability. The controllers where projected in order to not fully use the maximum speed of the wings. The maximum wing speed reached, without unexpected interferences, will be 2.5 flaps/s. The wings movement of the bird it will somehow approach to a sinusoidal function. To better understand the trajectory made by the bird we can see Fig. 21 (bird with initial values for weight and wing area).

8. CONCLUSION

The functionalities presented in this work are implemented on the simulator. In the other hand, we obtained some results that appeared to be satisfactory. That proves the development of the kinematical and dynamic model can show us the behavior of the bird.

After simulating all kind of actions like flapping wings, taking off, landing, and others we will implement a close loop with some controllers as well as planning trajectories allowing the bird to fly along an arbitrary path.

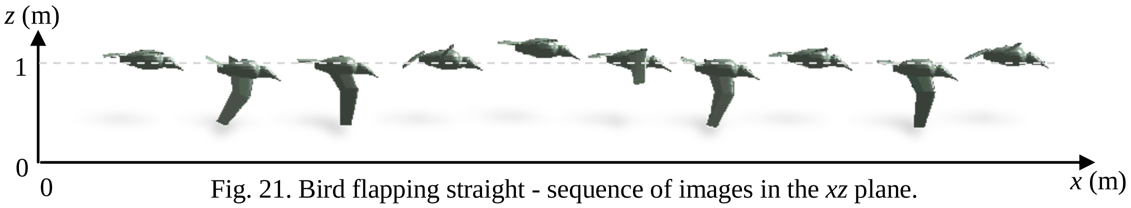


Fig. 21. Bird flapping straight - sequence of images in the *xz* plane.

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